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STRUCTURAL TOPOLOGY OPTIMISATION IN STEEL STRUCTURAL APPLICATIONS

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1. ABSTRACT

This study introduces applications of structural topology optimisation to buildings and civil engineering structures. Topology optimisation problems utilize the firmest mathematical basis, to account for improved weight-to-stiffness ratio and perceived aesthetic appeal of specific structural forms, enabling the solid isotropic material with penalization (SIMP) technique. Structural topology optimisation is a technique for finding the optimum number, location and shape of “openings” within a given continua subject to a series of loads and boundary conditions. Aerospace and automotive engineers routinely employ topology optimisation and have reported significant structural performance gains as a result. This paper examines two examples of where topology optimisation may be a useful design tool in civil/structural engineering in order to overcome the frontiers between civil engineers and engineers from other disciplines. The first example presents the optimised structural design of a geometrically complex high-rise structure, while the second one focuses on the optimisation and design of a perforated steel I-section beam, since such structural members are widely used nowadays in the vast majority of steel buildings.

2. INTRODUCTION

Structural optimisation is concerned with maximizing the utility of a fixed quantity of resources to fulfill a given objective. Three categories of structural optimisation exist; shape, size and topology. Structural topology optimisation is the most general of the three categories yielding information on the number, location, size and shape of “openings” within a continuum. The first solutions to a topology optimisation problem were presented by Michell [1]. Modern topology optimisation techniques can be applied to generalised problems through the use of the Finite Element (FE) method, as a relatively recent innovation. Aerospace, automotive and mechanical engineers have successfully utilised topology optimisation in order to achieve weight savings in structures. Enthusiasm for topology optimisation in the field of civil/structural engineering, where weight savings are seen as less critical due to the one off nature of building structures, is generally accepted as being more muted [2]. However, in the era of sustainable and resilient infrastructures, where the concept of redundancy plays a significant role, we should reconsider optimising every single structure to the best of its efficiency. Indeed the one off nature of every civil-structural engineering project necessitates the use of rigorous optimisation techniques to drive efficiencies on the increasingly complex projects of today.

Topology optimisation has found several novel applications in the field of civil engineering, most notably; a novel technique for geotechnical analysis [3] and reinforcement layout optimisation in concrete structures [4]. The main focus of this review study is applications of topology optimisation to the design of large scale buildings and structural engineering components.

3. TOPOLOGY OPTIMISATION IN ARCHITECTURE

During the 20th century architects and engineers have used innovative and novel methods to develop optimum forms of structures and sculptures. Of particular note would be the works from Antonio Gaudi, Félix Candela, Frei Otto, Pier Luigi Nervi, Heinz Isler, Richard Buckminster Fuller and Robert le Ricolais [5,6,7]. Whilst the techniques employed by these innovators generated efficient and aesthetic forms, they shared a common limitation. All of the techniques employed required that the number of holes within the structure had to be known apriori to the structural form finding exercise, which usually involves the use of a physical analogue model. Topology optimisation is not restricted by this limitation and it can effectively “carve” the optimum structure form from a block of material defined by the designer. In addition, the increased freedom of being able to optimize the number of openings within a structure offers an exciting new chapter in the study of improved structural forms.

4. TOPOLOGY OPTIMISATION IN HIGH-RISE BUILDINGS

Requirements for high-rise buildings as solutions to overcrowding in modern cities and as landmarks pose a significant challenge for structural engineers. This challenge is elegantly described by the “premium for height effect” [8] whereby the material required to construct taller buildings is disproportionately greater than for low-rise construction due to the increased bracing requirements. An even more significant structural challenge in the 21st century is the increasing tendency for architectural aspirations in high-rise construction to tend towards “aerodynamic”, “twisted” and “free” forms [9]. The geometric complexity of “twisted” and “free” form structures often causes engineering intuition to fail when attempting to determine the optimum structural layout. An overview of an investigation into the use of topology optimisation for the design of a geometrically complex high-rise structure, conducted by the authors, is presented.

In order to convince the civil engineering community to use the topology optimisation technique in the design of a geometrically complex high-rise structure a proposal for a tower with a "freeform" architectural intent was sought. The Bionic Tower is an architectural proposal for a high-rise tower in Abu Dhabi as it is shown in *Fig.1a*. The project reached the feasibility stage in 2007 but was never progressed. An investigation was conducted herein to determine how topology optimisation could have been used at the conceptual structural design phase.

A braced outrigger structural arrangement was selected for the Bionic Tower (*Fig. 1b*) whereby the structural core is stabilised by a series of structural elements on the perimeter of the building. The core is connected to the external bracing elements by a truss at the pinnacle of the tower. The braced outrigger was selected on the basis that it fulfills the architectural intent of an externally visible structure and provides a viable structural solution for a tower of this height. The core is connected to the perimeter columns by a series of horizontal trusses. Lateral loading was applied to the tower and topology optimisation studies were performed on the entire exterior surface as well as on the trusses connecting the core to the perimeter surface.

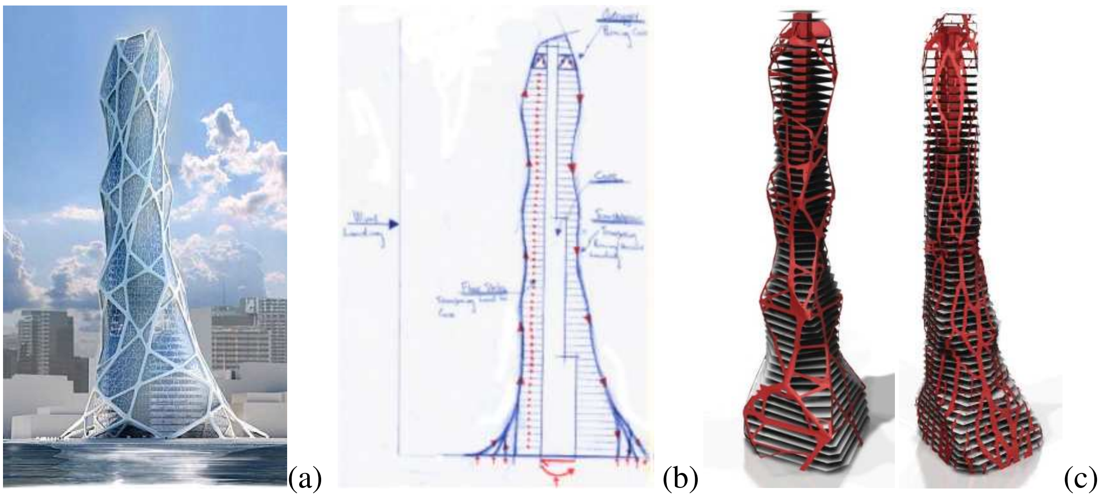

Fig. 1: (a) Bionic Tower proposal, (b) Current proposal, (c) Optimised proposal with wind loading only (left) and combination of wind and gravity loading (right)

Despite the highly irregular shape of the tower, it was found that a series of discrete structural load paths could be identified from the results of the topology optimisation (*Fig. 1c*). An inspection of the trusses connecting the core to the perimeter surface (*Fig. 2*) showed completely rational truss layouts with strong similarities to typical optimal truss layout solutions found in the literature. Furthermore, the aesthetics of its structural layout were compatible with the "freeform" architectural initial intent of the architect and the client. It is worth noting that the topology optimisation technique has been applied to the structural design of irregular and twisted high-rise structures previously; however the example presented is the first of its kind, where the topology optimisation has been applied to a completely "freeform" geometry. The results exemplify how topology optimisation is a useful design tool for designing structures for complex forms, where intuition may fail.

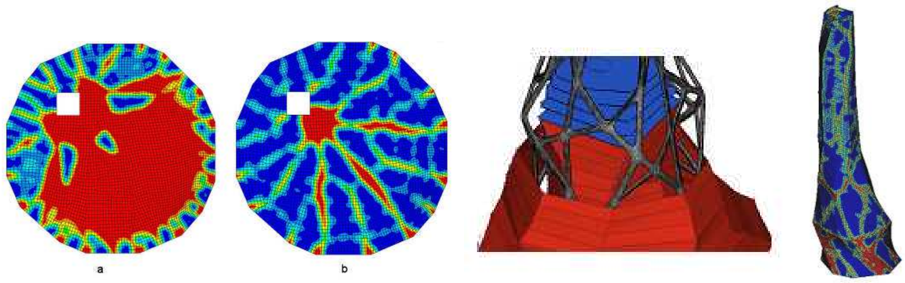

Fig. 2: Rational truss structures suggested for the outriggers in the results of the topology optimisation study

5. TOPOLOGY OPTIMISATION IN STEEL STRUCTURAL MEMBERS

The judicious placement of holes in the webs of steel beams has been employed to design lighter and stiffer beams for over 100 years. The original concept of creating a beam with web openings can be attributed to Geoffrey Murray Boyd [10], who patented what is now known as the castellated beam.

Castellated beams are formed by the expansion of a parent I-section to form a deeper stiffer section with web openings. Cellular beams, which contain circular openings, are currently the most widely used perforated beams due to their beneficial weight-to-stiffness ratio, and the ability to pass services (eg. hydraulic pipes, electric wires, etc.) through large holes, while the stresses are distributed evenly in the vicinity of the circular holes. An alternative to the castellation process of fabrication is the plate assembly. Plate assembly involves the fabrication of the I-section from a series of three flat steel plates (*Fig. 3*). Plate assembly has the advantage of increased flexibility in terms of the position and the shape of the openings.

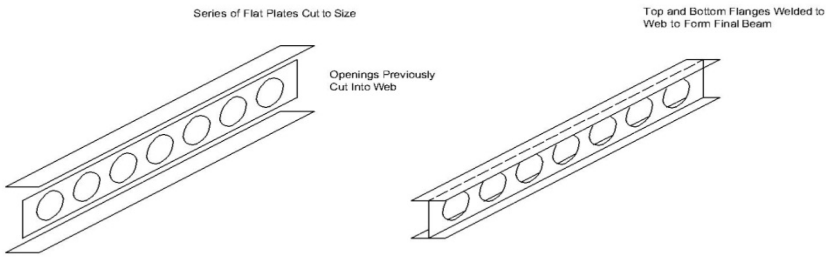

Fig. 3: Plate assembly fabrication for perforated beams

The constant desire for improvement and mature level of understanding of the structural action of perforated steel sections has recently led to novel opening shapes, such as ellipses, being investigated [11]. These novel opening shapes were proposed as they promote an efficient and economic castellated fabrication, improved structural performance and aesthetic qualities when compared to the standard opening types.

A comprehensive investigation was conducted with the use of topology optimisation techniques for the optimal design of the web openings in structural steel beams used in Civil Engineering applications [12]. The use of the continuum structural topology optimisation approach for the design of an I-section beam web has not previously been presented in the literature. The SIMP technique was implemented in this study. Various constraints and objectives were investigated.

The study was conducted on a standard 305x165x40 Universal Beam (UB). The section was selected on the basis that it has been widely used in prior to both experimental and numerical studies [13] and represents a typical 5m span section in building construction. The beam was subjected to uniformly distributed loading along the top compression steel flange.

The topology optimisation was performed on the beam web only with the objective of maximizing the stiffness of the beam subject to a constraint on the area of the beam web that must be massless. In perforated beams like this, the web plays a very important role in providing the vertical shear capacity, forming the so called Vierendeel mechanism as well as providing resistance to the out-of-plane web-post buckling failure mechanism [14]. Both these local failure modes are directly associated to perforated beams, hence the study of the web only. On the other hand, steel flanges are providing the global bending capacity and hence they are not considered in the current investigation. Initially, it was specified that a minimum of 60% of the beam web should be open (massless). The topology optimisation results (*Fig. 4a*) suggested a truss-like structure for the entire length of the beam, with a large opening in the centre where maximum moments but low shear forces exist. The overall design appeared to follow the lines of the principle stresses within the beam web and the openings took a rhomboidal shape. In order to rationalize the results of the topology optimisation, a complementary study was conducted where the results were constrained so as to be symmetrical about the longitudinal axis of the beam web. The symmetry constrained study resulted in a similar design with rhomboidal openings, but it was better balanced along the length of the beam (*Fig. 4b*).

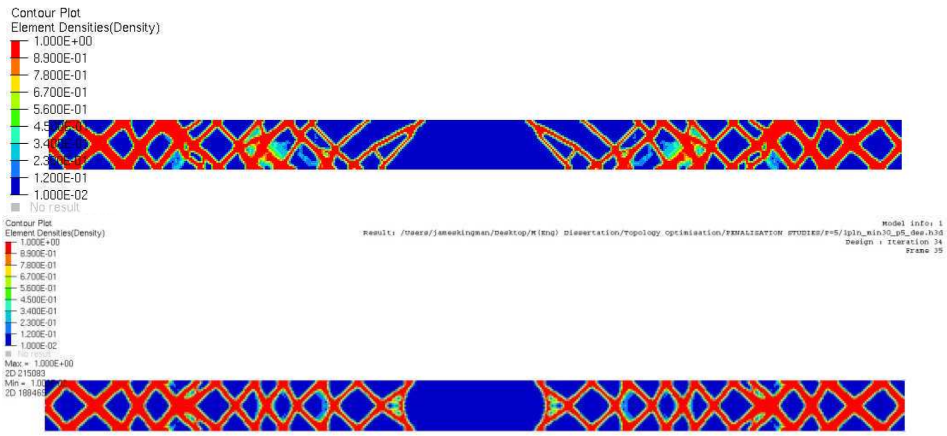

Fig. 4: (a) Results of a topology optimisation study on a beam web, (b) Results of a topology optimisation study on a beam web incorporating a symmetry constraint

The results of the topology optimisation study were post-processed in order to generate the finalised geometry of the optimised beam web (*Fig. 5*). In order to further investigate the structural performance of the beam web in comparison to a typical beam with circular web openings, a nonlinear FE analysis was employed. The size of the circular web openings was determined based on the maximum size generally used widely in industry, equal to 0.75 times the depth of the web. It was desirable to compare a cellular beam of a similar mass in order to be able to draw valuable conclusions regarding the structural efficiency of the topology optimised design.

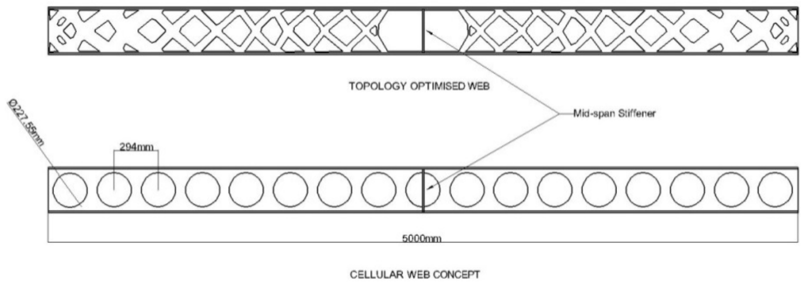

Fig. 5: Geometry of topology optimised beam web & Geometry of cellular beam web

The basis of the FEA method employed is a three-step process whereby an initial pre-stress is applied to the FE model and a linear static analysis performed. The results of the linear static analysis are then used in an eigenvalue analysis of the FE model to determine the first buckling frequency and its associated mode shape. Imperfections are applied to the FE mesh, using the scaled mode shape taken from the eigenvalue analysis. A geometric and materially nonlinear FE analysis is then performed to determine the load response of the beam. The results of the FE analysis (using ANSYS) suggest that the beam with an optimised web has a higher yield load and a greater stiffness in the linear range compare to the cellular beam [12]. Since both of the beams are formed from the same amount of structural material it can be concluded that the use of material in the topology optimised design is more efficient. The results also demonstrate that at the yield load level the stresses in the web of the cellular beam increase towards the support, oppositely to the optimised web, which were uniform particularly close to the critical area of the supports.

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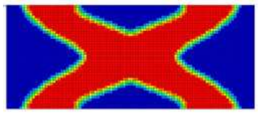	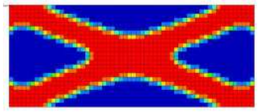	
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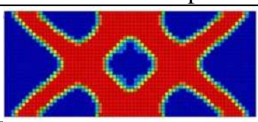	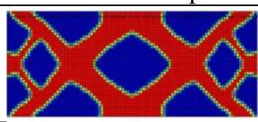	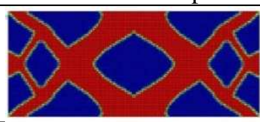
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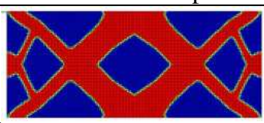	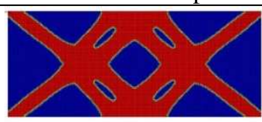	

Fig.6: 1 Results of topology optimisation on localised beam sections of varying depths

As the resulting optimised design was generally complex and somewhat difficult to justify and be used in most practical applications, a localised study approach was established in order to identify optimum web opening shapes. In the local study a short beam section was modelled while shear forces and bending moments applied directly to the section and the topology optimisation was then performed. Further, a parametric investigation on a large number of cross-sections indicated that only the depth of the section alters the optimal topology of the web openings (*Fig. 6*). It can be concluded that for beams of depth between 270mm and 700mm, the optimum web opening topology is the same. Based on the results of the local study a novel opening architecture has been suggested (*Fig. 7*). It is anticipated that this new configuration is possible to be fabricated using the plate assembly technique, while no cost implies, compared to any other opening shapes.

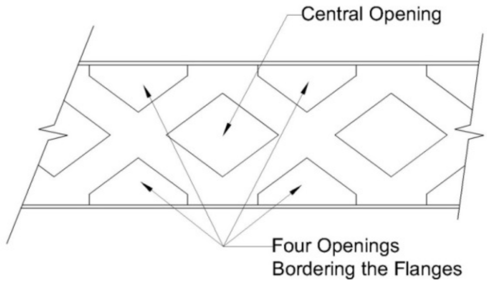

Fig.7: 2 Suggested web opening configuration

6. CONCLUSIONS

Topology optimisation offers significant opportunities in civil/structural design and architecture. It has been suggested as a tool that can lead to greater collaboration between engineers and architects during the conceptual design process. A limited number of examples of topology optimisation being used in structural engineering and architecture can be found in the literature and have been presented in this paper. At present, the major barriers to the widespread implementation of topology optimisation methods are: (i) the complex geometry of the optimised designs and (ii) the difficulty in solving problems involving nonlinear behaviour (such as buckling) and dynamics. The increasing use of advanced manufacturing techniques such as CNC machining and 3D-printing may offer a solution to the complex geometry often arising during topology optimisation studies. Methods for solving topology optimisation problems involving nonlinear behaviour as well as dynamics are currently under investigation with a promising area of research being the Equivalent Static Load (ESL) method.

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ΤΟΠΟΛΟΓΙΚΗ ΒΕΛΤΙΣΤΟΠΟΙΗΣΗ ΣΕ ΜΕΤΑΛΛΙΚΕΣ ΚΑΤΑΣΚΕΥΑΣΤΙΚΕΣ ΕΦΑΡΜΟΓΕΣ

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ΠΕΡΙΛΗΨΗ

Η παρούσα μελέτη εξετάζει μια σύγχρονη και πολλά υποσχόμενη νέα εφαρμογή, αυτή της τοπολογικής βελτιστοποίησης σε κτίρια και γενικότερα σε έργα πολιτικού μηχανικού. Η λύση σύνθετων προβλημάτων βελτιστοποίησης, υπό το πρίσμα του εκτενούς υπόβαθρου της τοπολογίας, επιστρατεύει καλά θεμελιωμένες μαθηματικές αρχές και εργαλεία αποσκοπώντας για παράδειγμα στη βελτίωση της αναλογίας βάρους-δυσκαμψίας σε δομικά στοιχεία, ή επίσης στη πρόσδοση ιδιαίτερης αισθητικής σε αυτά. Η τοπολογική βελτιστοποίηση με απλά λόγια είναι μια τεχνική που στοχεύει στην εξεύρεση του βέλτιστου αριθμού, θέσης και σχήματος των «ανοιγμάτων» σε ένα συνεχές σύστημα ενώ αυτό υπόκειται σε μια σειρά δεδομένων συνδυασμών φορτίσεων και συνοριακών συνθηκών. Ιδιαίτερα στην αεροναυπηγική και την αυτοκινητοβιομηχανία υψηλών επιδόσεων (π.χ. Φόρμουλα 1) η μέθοδος της τοπολογικής βελτιστοποίησης χρησιμοποείται ευρέως εδώ και αρκετά χρόνια, με ξεκάθαρα οφέλη σε επίπεδο κόστους και απόδοσης. Στην ερευνητική παρουσίαση που ακολουθεί εξετάζονται δύο παραδείγματα όπου η εν λόγω μέθοδος αποδεικνύει την ικανότητα της να αποτελέσει στο μέλλον ένα πρώτης τάξης εργαλείο σχεδιασμού δομικών κατασκευών, καταρρίπτοντας τα όποια νοητά σύνορα μεταξύ πολιτικών μηχανικών και μηχανικών άλλων ειδικοτήτων. Το πρώτο παράδειγμα παρουσιάζει μια βέλτιστη σχεδίαση ενός γεωμετρικά περίπλοκου πολυώροφου κτιρίου, ενώ το δεύτερο εστιάζει τοπικά στη βελτιστοποίηση του σχεδιασμού μίας χαλύβδινης διάτρητης δοκού διατομής-I, ένα δομικό στοιχείο με εκτεταμένη και πολύ δημοφιλή χρήση στην πλειονότητα των μεταλλίκων κτιρίων του σήμερα.